Signal Processing and Renewable Energy
June 2020, (pp. 53-72)
ISSN: 2588-7327
eISSN: 2588-7335

Compensating and Enhancing Voltage Quality in Electrical Distribution Systems Using Dynamic Voltage Restorer Based on Synchronous Reference Frame Theory

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Received: 14-Feb-2020, Revised: 22-Mar-2020, Accepted: 26-Mar-2020.

Abstract

One of the common problems of power quality is the occurrence of voltage sags due to different types of balanced and unbalanced short-circuit faults in electrical distribution systems. Dynamic Voltage Restorer (DVR) is the most effective equipment used for voltage recovery in power distribution systems and it injects voltage in series with line voltage for voltage recovery. In this paper, the structure and general components of this equipment are presented. In addition, by applying a control scheme based on Synchronous Reference Frame Theory (SRFT) in its control system, the effective role of this equipment in compensating and maintaining the voltage of a power distribution system under the occurrence of balanced three-phase short-circuit fault and unbalanced single-phase to ground short-circuit fault is investigated and analyzed using Simulink/Matlab software.

Keywords: Short Circuit Fault, Power Quality Improvement, Voltage Sag, Dynamic Voltage Restorer (DVR), Synchronous Reference Frame Theory (SRFT).

1. INTRODUCTION

Researches show that the equipment expanded in the last two decades is highly sensitive to the quality of the supply, and large industrial consumers have reported a large number of major economic losses caused by the decline in the power quality. One of the most important problems in the power quality of power distribution systems is the occurrence of voltage sags, which is one of the most important challenges for electricity distribution companies in respect of

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advanced industries. One of the causes of voltage sag is the occurrence of various short-circuit faults in the power distribution system [1].

Custom Power or D-FACTS devices have been introduced as equipment based on power electronic for controlling distribution systems and improving the power quality of electrical distribution systems. The structure and topology of some of these devices are presented in [2-5]. One type of device used to correct voltage Sags in distribution systems is Dynamic Voltage Restorer (DVR) which the components and topology of this device are introduced in [6-11]. The purpose of DVR is to protect sensitive loads from system disturbances. In the event of a fault, this equipment injects a voltage equal to the difference between the pre-fault voltage and the voltage during the fault by supplying the active power required from the DC power supply and the reactive power, and maintaining the load voltage in the range prior to the fault. When the voltage is injected into the distribution feeder in series with the compensator, the voltage is kept constant in the load terminals against the power quality disturbances on the source side. Quality of the compensation and quality of the injected voltage depend on the type of control used in this compensator. In this paper, the control technique based on synchronous reference frame theory, which is one of the most effective control methods for compensators, is used. Furthermore, by applying this control scheme to the DVR structure, the effective role of this equipment in compensating voltage of a power distribution system is examined and analyzed in the event of short circuit faults.

The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. The general requirement of a control scheme is to obtain an ac waveform with minimum total harmonic distortion (THD) and best dynamic response against supply and load disturbance when the DVR is operated for voltage sag compensation. There are different control techniques being used for the calculation of request voltage for compensator. In [12-14]. A control scheme based on RMS value of voltage has been implemented to control the two-level VSC used in the DVR and D-STATCOM. This control system only measures the RMS voltage at the load point. Using RMS value calculation of the voltage to analyze the sags does not give fast and suitable response and also it does not give accurate results and in during compensation, it cannot recover load instantaneous voltage accurately. Also, using this technique will significantly increase the total harmonic distortion (THD) of the load compensated voltage [14]. In [15, 16], the difference between the reference voltage and the voltage injected by compensator is used to produce the load rated voltage. When the source voltage is within the nominal range, the DVR always injects a small amount of voltage into the system. Due to this problem, applying this method to the DVR control system may result in the failure to determine the exact voltage needed to compensate during the event of fault in the system and there may always be some deviation in the injected voltage. As well as the problem outlined, the system does not respond well when compensating for different voltage disturbances. Another technique used to control this compensator and other similar compensators is the instantaneous reactive power theory (p-q technique) [17-20]. One of the disadvantages of this method is that the unbalanced voltage or current results in incorrect calculation of the reference signals are produced by the compensator [20].

Hence, for proper voltage sag compensation, it is necessary to derive suitable control scheme for inverter switching. In this paper, the control technique based on synchronous reference frame theory, which is one of the most effective control methods for compensators, is used and by applying this control scheme to the DVR structure, the effective role of this equipment in compensating voltage of a power distribution system is examined and analyzed in the event of short circuit faults. Also, the VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. The proposed compensator amends both balanced and unbalanced voltage sags and injects the appropriate voltage component to correct any voltage sag rapidly and to keep the load voltage balanced and constant at the nominal value.

2. STRUCTURE AND COMPONENTS OF THE DYNAMIC VOLTAGE RESTORER (DVR)

Dynamic voltage restorer is used to protect loads and to prevent disturbances on the supply side from reaching sensitive loads. The overall structure and topology of this device is shown in Fig. 1 [22].

The main components of this device are as follows [23, 26]:

A) Power Storage Unit: This unit is responsible for DC power storage and thus provides the active power required for DVR compensation.

B) Inverter or voltage source converter (VSC): A pulse-width modulation inverter is generally used. The main task of the DC voltage converter is to convert the DC voltage provided by the AC to AC voltage source.

Often three-phase two-level inverters are used. Each leg is switched according to pulse width modulation. In the case of switching with the main frequency switching, the switches are ON for a 180-degrees period with a 50% duty cycle. The structure of the inverter, switching and output waveforms in the switching mode with the main frequency are shown in Figure (2).

C) Passive Filter: Passive filters are used to convert the PWM pulse waveform to a sinusoidal waveform. By inserting the filter at the inverter output, the higher order harmonic components produced by the DC to AC conversion are eliminated in the voltage source inverter [23]. As shown in Figure (3), these filters can be mounted either on the high voltage side or on the low voltage side of the injection transformer.

D) Bypass switch: A bypass switch is used to protect the inverter from high currents when a fault or short circuit occurs downstream.

F) DC capacitor: This unit is responsible for keeping the DC input voltage of the inverter constant.

E) Coupling or Injection Transformers: In a three-phase system, the coupling transformer can be a single three-phase transformer or three single-phase transformers with proper connections.

The tasks of injection transformers are to isolate the DVR from the network voltage and increase the voltage level generated by the DVR. These transformers are connected in series to the distribution system and are known as injection transformers, boosters, couplings. The high voltage side of the injection transformer is connected in series to the distribution grid, while the low voltage side is connected to the DVR power circuit. For the three-phase DVR, the three single-phase transformers can be connected in a delta/open or wye/open structure as shown in figure (4) [23].

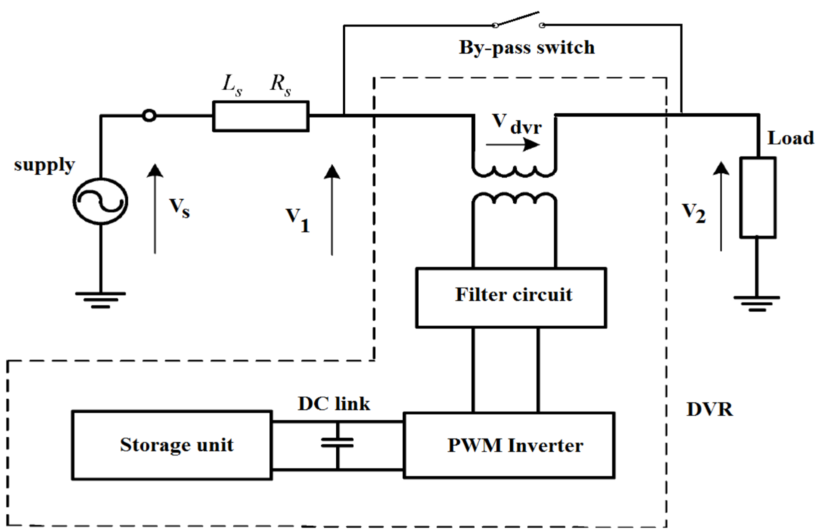

Fig. 1. The overall structure and topology of the DVR.

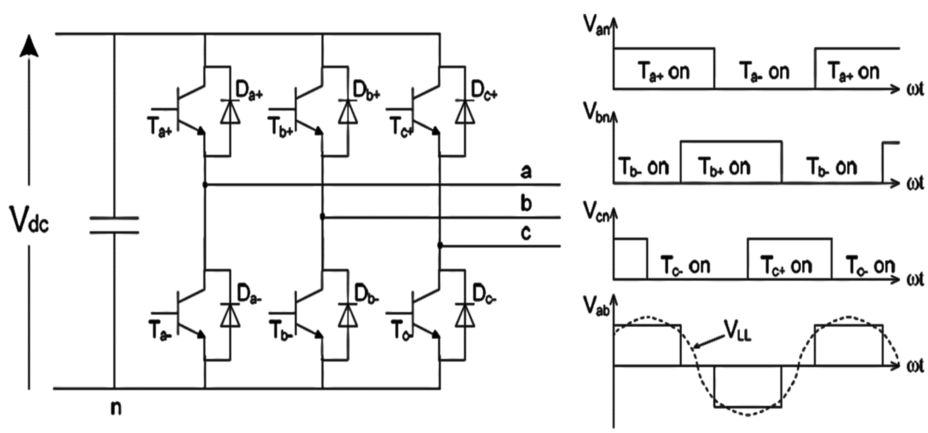

Fig. 2. Structure of the three-phase two-level inverter and its order of switching.

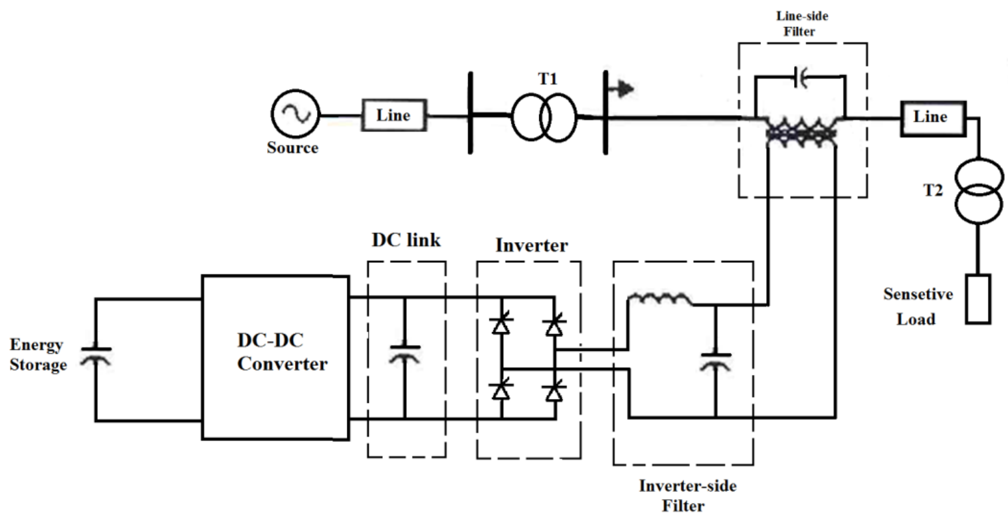

Fig. 3. Filters used in DVR.

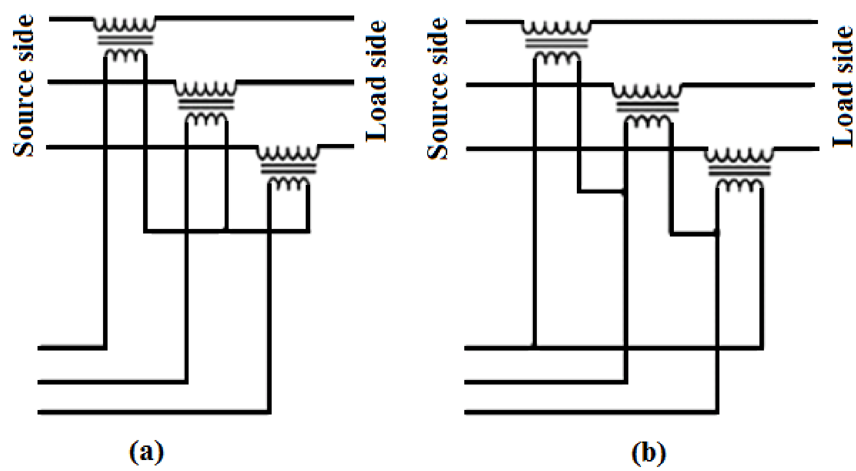

Fig. 4. Connection of primary side of the injection transformer a) wye/open structure b) delta/ open structure.

In the three-phase transformer with Wye/open connection, the primary windings are connected in the form of Wye (Y) and the secondary windings are not connected in the form of Wye or Delta or Zig-Zag and all three secondary windings are connected separately and directly to the grid as shown in Figure (4.a). Similarly, in the three-phase transformer with Delta/open connection, the primary windings are connected in the form of Delta (Δ) and the secondary windings are not connected in the form of Wye or Delta or Zig-Zag and all three secondary windings are connected separately and directly to the grid as shown in Figure (4.b).

The structure of the winding in the injection transformer is essentially dependent on the upstream distribution transformer. If the distribution transformer connection is either Δ/Y with ground neutral or not grounded or Y/Y with a ground connection or Δ/Δ, during an unbalanced fault or a ground fault on the high voltage side, no zero sequence current flows in the transformer secondary. For this reason, in the systems with the mentioned connections, an injectable transformer that only passes through the positive and negative sequence components is sufficient. As a result, the delta/open transformer can be used. For other winding connections, distribution transformers such as Y/Y on both sides of the ground, in an unbalanced fault, all three components of negative, positive and zero sequence flow to the secondary. Therefore, in this case, the wye/open transformer should be used as shown in Figure (4a) so that all three sequences can cross [23].

3. DVR FUNCTION IN VOLTAGE SAG CORRECTION

The main task of the DVR is to dynamically inject voltage into the system to compensate for and improve the voltage waveform, thereby controlling the amplitude and phase voltage of the load by injecting voltage into the grid. Its performance is very fast. For example, when a voltage Sag occurs mainly due to a short circuit fault in the adjacent feeders, the DVR can quickly compensate voltage Sag and then the end-user does not feel any Sag.

As shown in figure (5), if thevenin equivalent of the system is considered, voltage injected by DVR is obtained by the relation (1) [24-26].

$$V_{DVR} = V_L + Z_{th} I_L - V_{th} \quad (1)$$

And the load current I_L is equal to:

$$I_L = \left[\frac{p_L + jQ_L}{V_L} \right]^* \quad (2)$$

If the load voltage phase V_L is set to zero, the injected voltage is calculated as follows [24-26]:

$$V_{DVR} \langle \alpha = V_L \angle o + Z_{th} I_L \angle(\beta - \theta) - V_{th} \angle \delta \quad (3)$$

where α, β and δ are the angles of V_{DVR}, Z_{th}, and V_{th}, respectively, and θ is the angle of the load power factor that it is obtained from the relation (4).

$$\theta = \tan^{-1}(q_L / P_L) \quad (4)$$

Power injected by DVR is equal to [26]:

$$S_{DVR} = V_{DVR} I_L^* \quad (5)$$

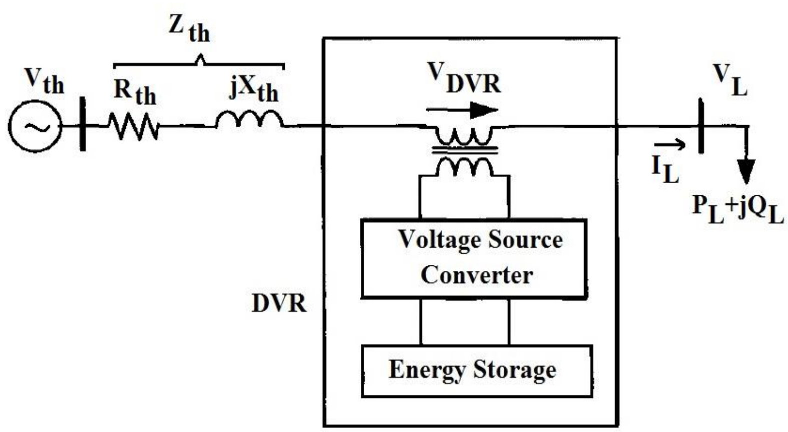

Fig. 5. Equivalent circuit of DVR and grid.

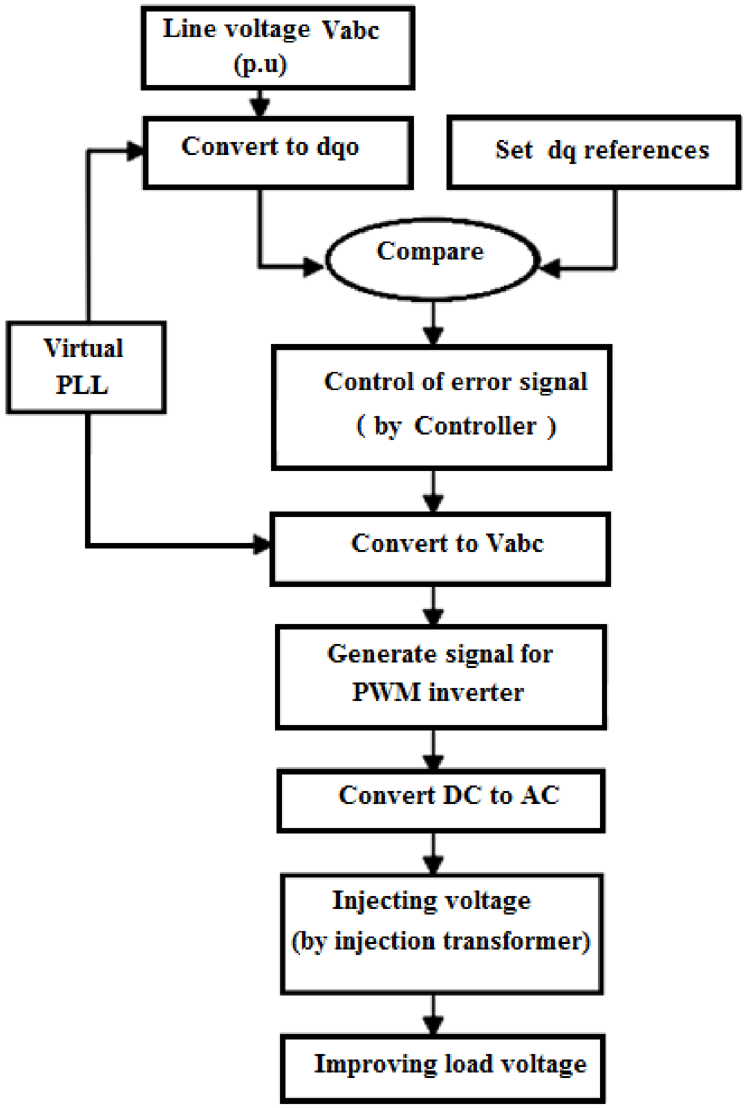

Fig. 6. Flowchart of the control scheme based on synchronous reference frame theory.

If the angle between V_{DVR} and I_L is kept upright, the injected active power will be zero for voltage compensation and only the reactive power will be injected by the DVR. Injected active power is provided by the DVR from the DC storage source [26].

The rated voltage of the DVR is calculated according to the maximum value of the voltage sag that it can be correct. The maximum value of the voltage sag and the maximum duration of the voltage sag determine the compensator capacity.

4. CONTROL SCHEME BASED ON SYNCHRONOUS REFERENCE FRAME THEORY

The DVR control system performs the task of detecting voltage Sag, calculating the corrective voltage, generating trigger pulses for voltage source converter and correcting any abnormal conditions in the series voltage injection, and terminating the trigger pulses when the fault is resolved. There are many control methods for DVR control. One of the best and most effective of the methods being the Synchronous Reference Frame (SRFT) Based technique or dq0 technique, in which phase lock loop (PLL) and park conversion or dqo are used to control DVR [21, 27, 28]. Figure 6 shows the flowchart of the synchronous reference frame-based technique for detecting voltage Sag.

Equation (6) expresses the conversion of the three-phase abc system to the dqo synchronous frame.

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (6)$$

where Θ is angle between phase A and d axis. In the first step, the voltage is converted from the reference frame a-b-c to the reference d-q-o. For simplicity, the zero-phase sequence component is ignored. Detection is performed in all three phases. The control scheme used is based on a comparison of the reference voltage and the measured terminal voltage. The fault signal is used as phase modulation and generates a commutation pattern for the power switches in the inverter. The commutation or switching pattern is performed by the sinusoidal pulse width modulation (SPWM) technique. Voltages are controlled by modulation. The PLL circuit is used to generate a single-phase sinusoidal wave with main voltages. In fact, the rotating angle between the d and q axes is generated by the PLL and at any given moment the phase angle is controlled to generate a voltage coincident with the power system. The control system provides excellent voltage regulation.

Figure (7) shows the control scheme implemented in Matlab/Simulink.

The controller system input is the load voltage, in per-unit (voltage of bus 3 in power distribution system under study as shown in figure 8). The load voltage is then transformed in d-q form. The voltage sag is detected by measuring the error signal (error between the reference values and the dq-voltage). The q-reference is set to zero and the d-reference is set to rated voltage. The d-q components of load voltage are compared with the reference values and the error signal is then entering to PI controllers. Two PI controller blocks are utilized for error signal-q and error signal-d separately. For error signal-d, Kp is set to 35 and Ki is set to 125 and for error signal-q, Kp and Ki is set to 20 and 235 respectively. All the coefficients selected use to tune up the error signal d and q so that the signal is stable and well responses to system disturbances. The outputs of the controllers then are converted to Vabc form before forwarding to pulse width modulation (PWM) block.

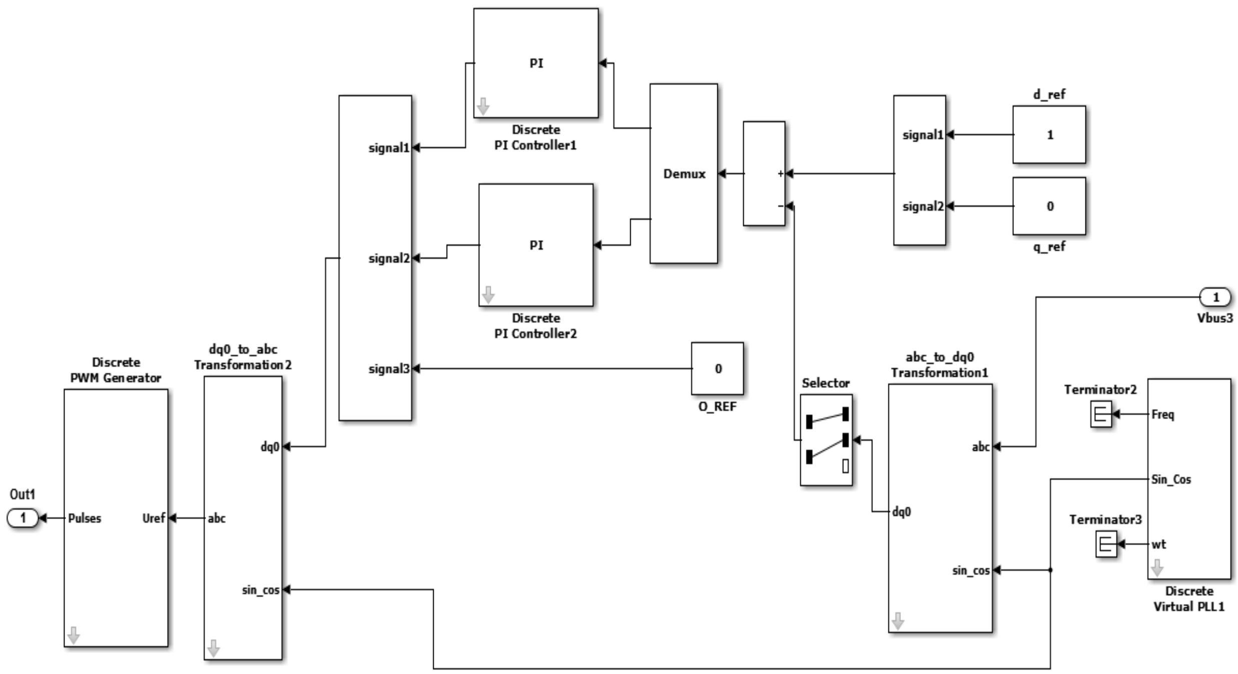

Fig. 7. Control scheme implemented in Matlab/Simulink.

The control system has the ability to improve the load voltage back to 1 per-unit before delivering it to the load in balanced and unbalanced fault conditions. Even for worst case (three phase faults with severe voltage sag), DVR controlled by PI controllers still can work successfully. The proposed control scheme possesses very good transient and steady-state performances for various kinds of voltage disturbances.

When the power system characteristics such as system resistance, system inductance, short circuit current, power system capacity and etc. are partially changed, in case of a fault, the magnitude of the voltage sag caused by the fault is changed. However, the proposed compensator performance is not affected by minor variations in these parameters, and under severe voltage sags conditions, or even under power supply interruption conditions, it is able to inject the required voltage to restore the load voltage completely. If power system characteristics and parameters change significantly, the compensator may not inject the voltage to the required magnitude. In this situation, controllers need to be re-set to avoid instability. In this condition, the new coefficients of controllers use to tune up the error signal d and q so that the signal is stable and well responses to system disturbances.

5. SIMULATION AND RESULTS

5.1. Sample System Under Study

In this section, the power distribution system of an industrial plant with the presence of the DVR is simulated using Simlink/Matlab software and simulation results are presented as well. Single line diagram of the sample power distribution system with a DVR is shown in figure (8).

In the simulations, the upstream grid is equated using a 20KV thevenin equivalent circuit with a frequency of 50Hz (Upstream bus 1). Medium voltage loads and distribution transformers are fed through bus 1. The LV loads are fed through two transformers 20/0.4 kV (bus 2&3).

The data and parameters used in the simulations are given in Tables 1-2.

5.2. Simulation Results

In the first step, at the 20 kV side of the system (the primary side of the 20 / 0.4 kV transformer), a single phase to ground short circuit fault occurs. The simulation results for this case, with and without the presence of the DVR are shown in Figures (9) to (13).

As a result of single phase fault to ground, the voltage of 400V bus loads (bus 2 and 3) drops by 30% which is quickly

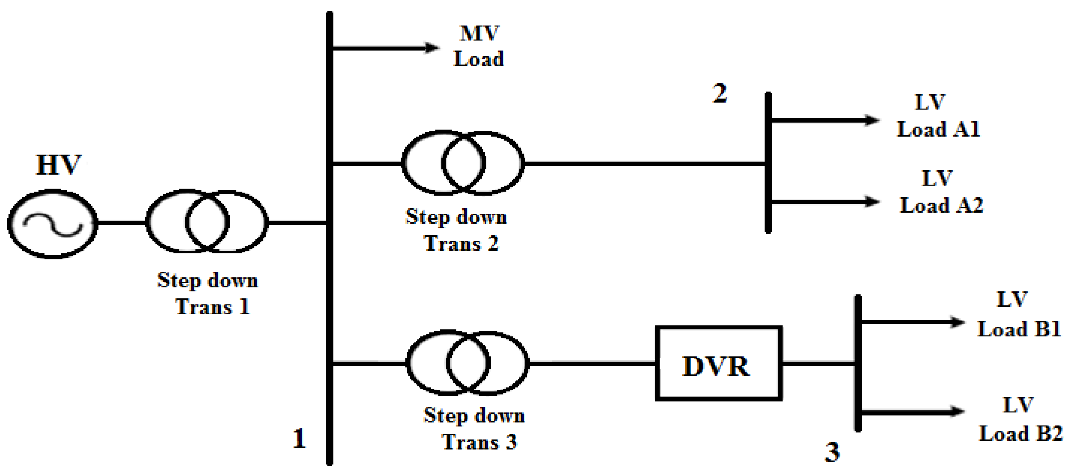

Fig. 8. Single line diagram of sample power distribution system under study.

Table 1. ***DVR parameters.***

Parameters	Values
DC-link voltage	500 V
Type of VSC	Two level, three-phase
Type of injection transformer	Three single-phase transformer
Connection and injection transformer ratio	Grounded wye/open, 1:1
Leakage reactance of injection transformer	10%
Passive filter	0.005 Ω, 5 mH
Switching frequency	3 kHz

Table 2. ***System parameters.***

Parameters	Values
Upstream system voltage and frequency	132 kV
System frequency	50 Hz
System impedance	0.1+0.755j
Parameters of step down transformer 1	132/20 kV, 15 MVA uk%=11.82
Parameters of step down transformer 2	20/0.4 kV, 1500 kVA uk%=5.39
Parameters of step down transformer 3	20/0.4 kV, 1500 kVA, uk%=5.35
LV load A1, A2	400 kW
LV load B1, B2	400 kW
Load power factor	0.85 lagging

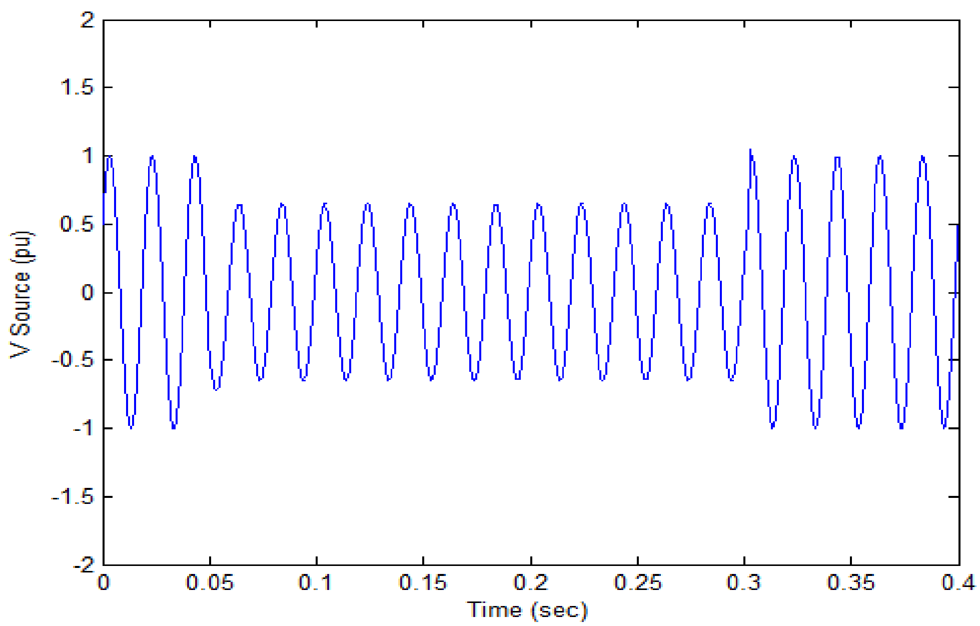

Fig. 9. Voltage of Phase A in bus 2&3 due to single phase fault to ground without DVR.

compensated by DVR. In this case, the system will inject enough power to correct x the DVR voltage. As a result of switching on power electronic devices and using DC source, harmonics are injected into the grid and since these devices are also used in the DVR, in addition to voltage compensation and recovery, a certain amount of harmonic is also injected into the grid which increases the percentage of THD becomes the system.

The total harmonic distortion (THD) generated by applying a passive filter to the output of the DVR inverter can be easily reduced. From the obtained frequency spectrum, it can be seen that the percentage of THD load-side voltage due to injected voltage by DVR is 1.65%, although this value is within the standard range (below 5%), It decreases further with higher values of inductor in passive filter of the DVR.

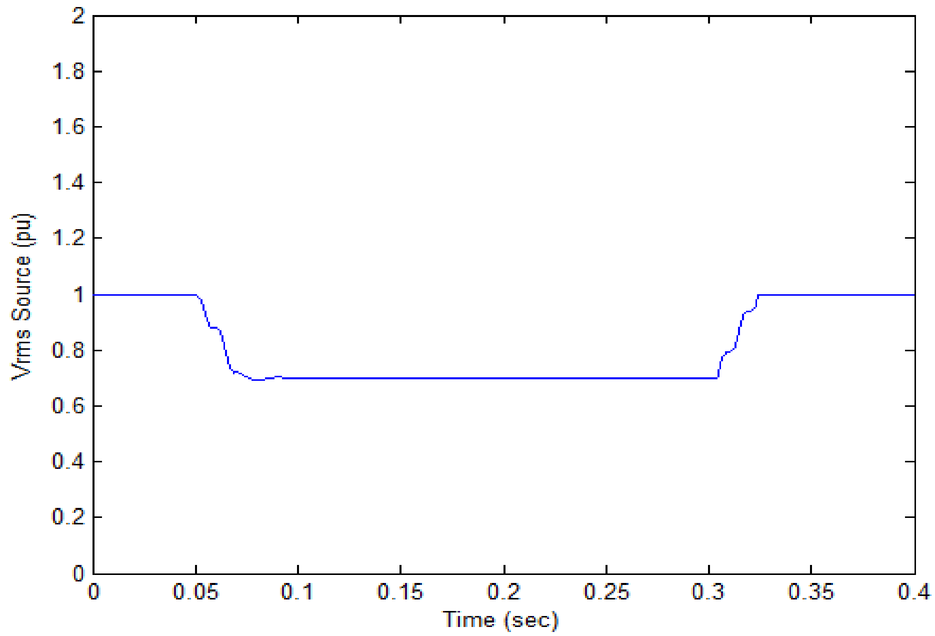

Fig. 10. Voltage effective value of bus 2&3 due to single phase fault to ground without DVR.

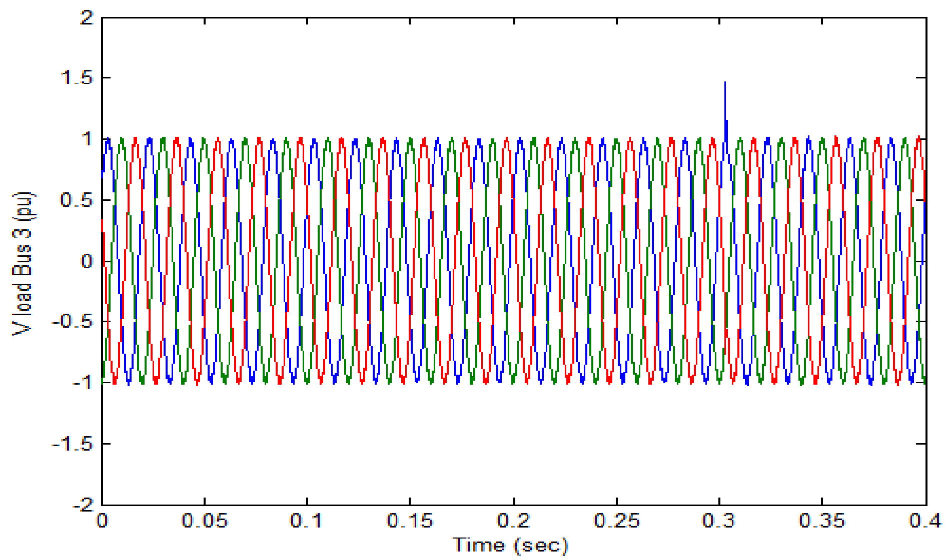

Fig. 11. Modified voltage of bus 3 due to single phase fault to ground with DVR.

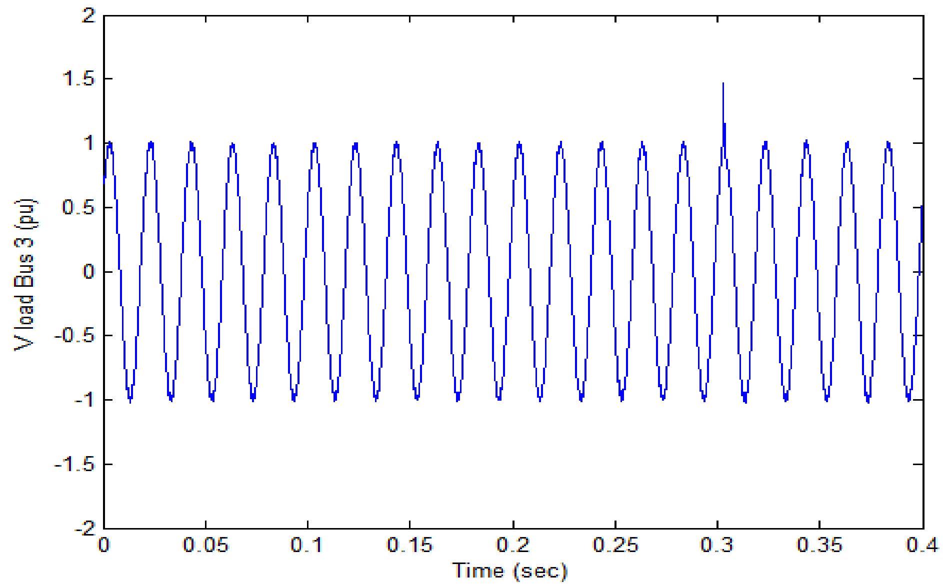

Fig. 12. Modified voltage of Phase A in bus 3 due to single phase fault to ground with DVR.

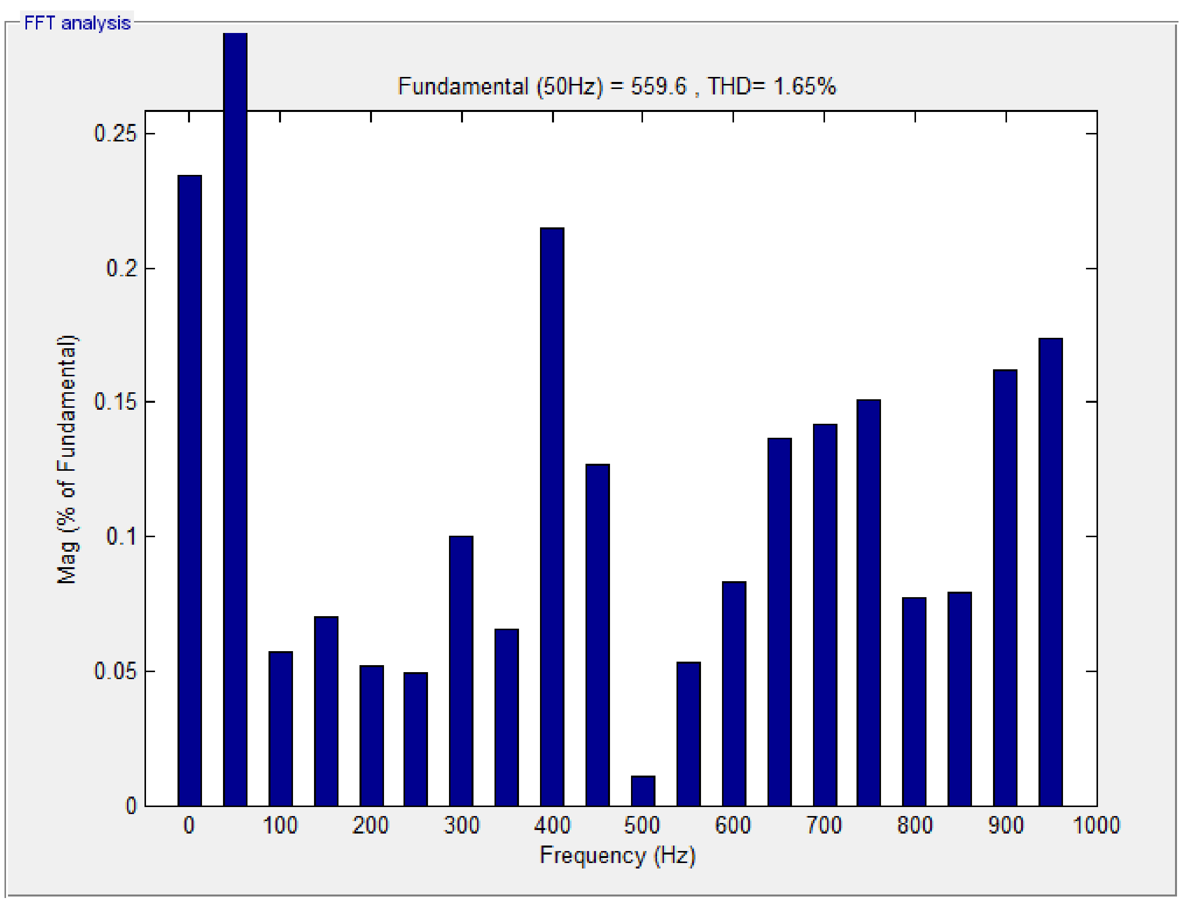

Fig. 13. Frequency spectrum of modified voltage in bus 3 due to single phase to ground fault with DVR.

Next, on the 20KV side of the grid (the primary side of the 20 / 0.4kV transformer), a three-phase short circuit fault occurs. When this fault occurs, the secondary voltage of the transformers 20/.04 kV at bus 2 and 3 drops by 80%. Simulation results in state of the three-phase short circuit fault, with and without the presence of DVR, are shown in Figures (14) to (20).

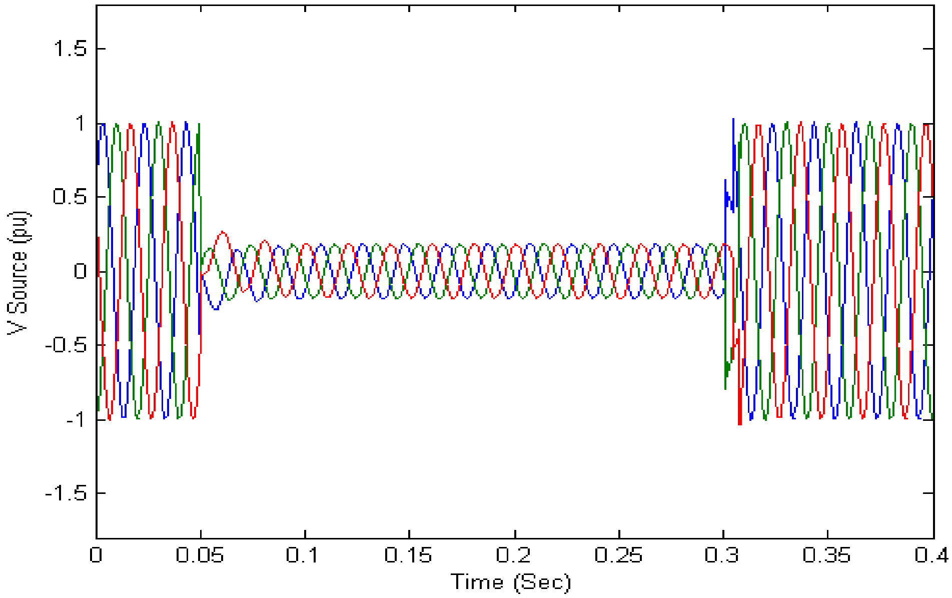

Fig. 14. Voltage of bus 2&3 due to three phase fault without DVR.

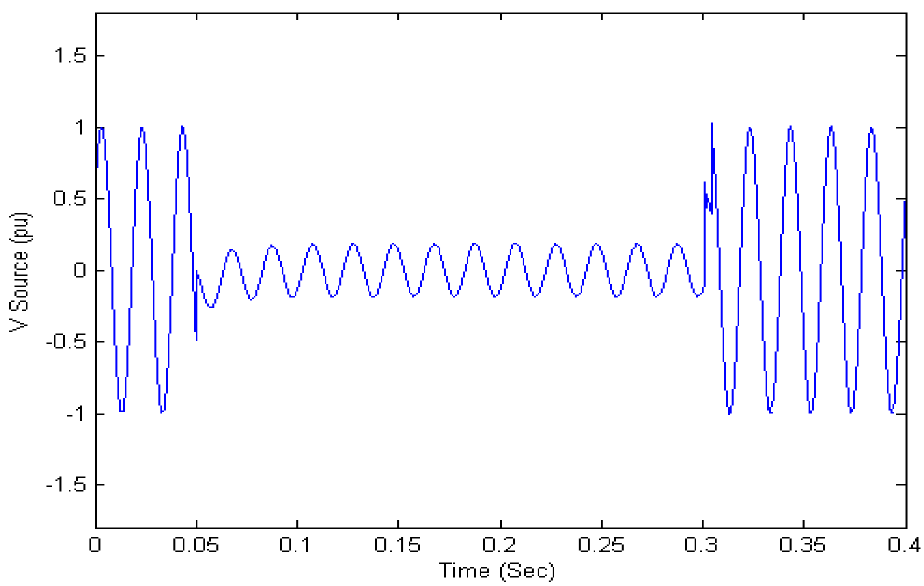

Fig. 15. Voltage of Phase A in bus 2&3 due to three phase fault without DVR.

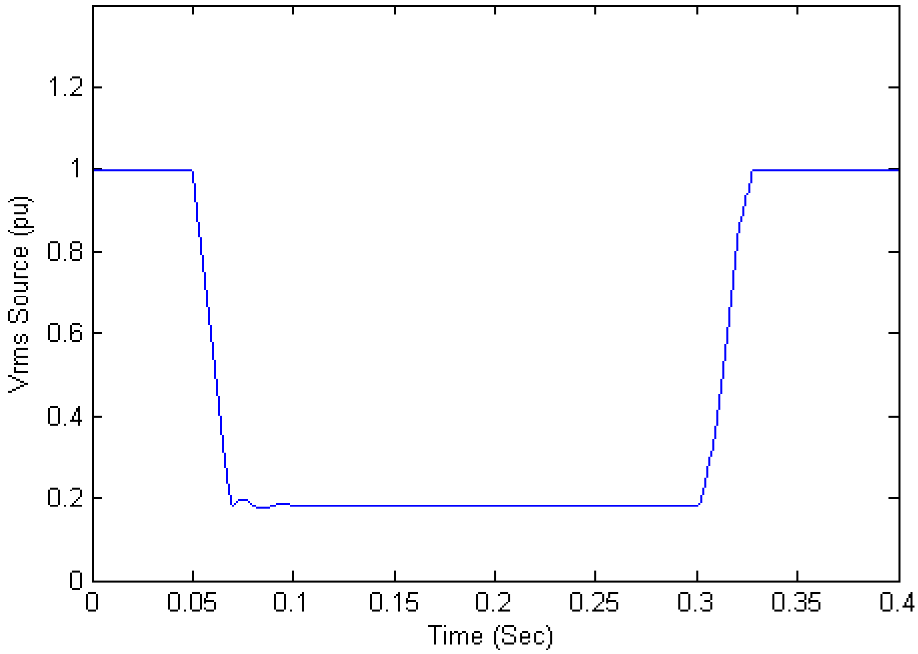

Fig. 16. Voltage effective value of bus 2&3 due to three phase fault without DVR.

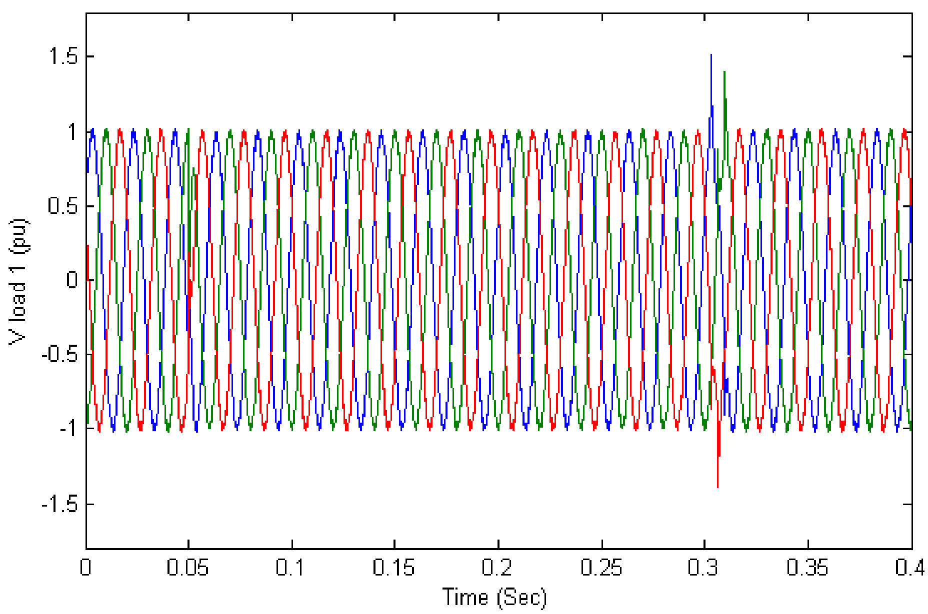

Fig. 17. Modified voltage of bus 3 due to three phase fault with DVR.

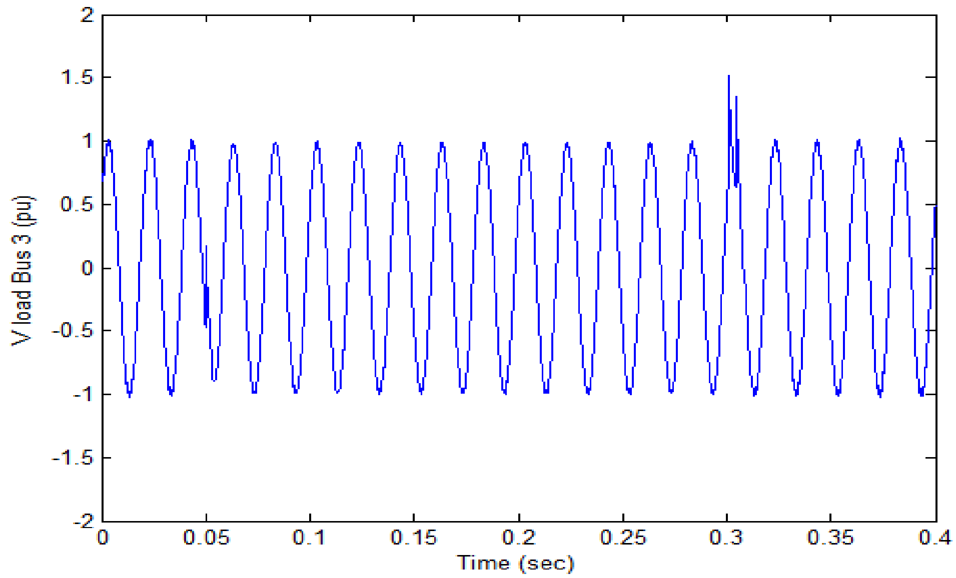

Fig. 18. Modified voltage of Phase A in bus 3 due to three phase fault with DVR.

As a result of a three-phase fault, the load voltage in 400 V buses drops by 80%, which is compensated by the DVR, and the voltage of bus 3 is restored to the value of 99.1% before the fault. In this case, the DVR injects more power to the system than the single-phase to ground fault for correcting voltage. In this case, the THD value of the load side voltage due to voltage injected by DVR is 1.96% which is also within the standard range.

Due to event of the short-circuit faults, voltage drops in the upstream power system buses as well as in the distribution system buses. The compensator based on proposed control system, injects the suitable voltage in proportion to the value of voltage sag as much as difference of before and during the sag so that the voltage of the protected sensitive loads is recovered to the nominal value. The injected voltage by the compensator during the three-phase fault is shown in Figure (20).

The simulation results of the both scenarios show that the proposed scheme modifies the sag quickly and provides excellent voltage regulation. The compensator with proposed scheme handles all types, balanced and unbalanced fault without any difficulties and injects the appropriate voltage component to correct any fault situation occurred in the supply voltage to keep the load voltage balanced and constant at the nominal value. Both scenarios show an excellent performance and generate low THD (below 5%).

6. CONCLUSION

In this paper, by implementing and simulating a DVR based on synchronous reference frame using Simulink software and applying this equipment in one of the low voltage buses of a typical power distribution system, the effect and role of this equipment in modification,

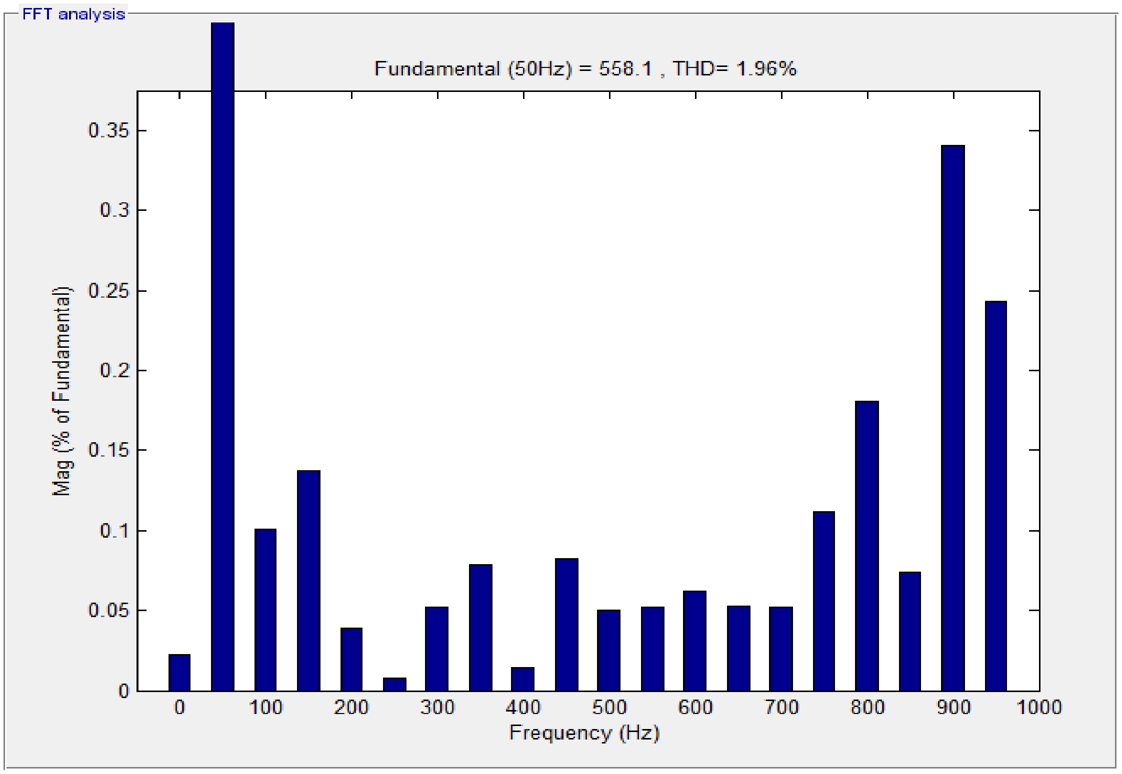

Fig. 19. Frequency spectrum of modified voltage in bus 3 due to three phase fault with DVR.

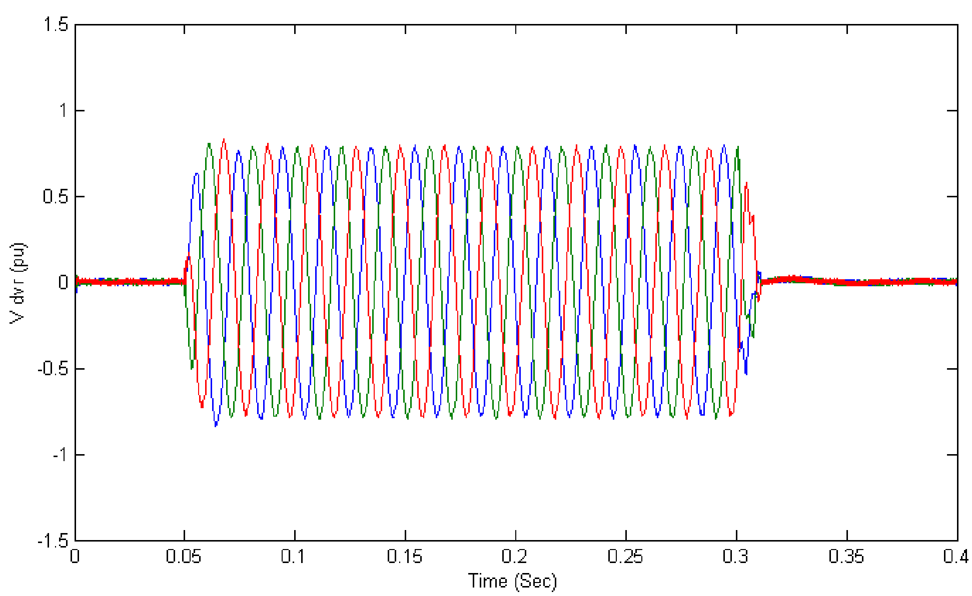

Fig. 20. Injected voltage.

compensating and stability Voltage, and in general to improve the power quality of this power distribution system, were studied and analyzed. It has the capability to compensate for balanced and unbalanced voltage Sag. The simulation results show that this equipment plays a very important role in voltage recovery and restores the reduced voltage very quickly. Therefore, in power distribution systems of industries with sensitive loads due to the frequent occurrence of voltage Sag and various factors such as starting inductive loads, energizing power transformers and occurrence of short circuit faults, it is recommended to maintain the voltage supply of sensitive loads in the normal range. This equipment should be installed in a suitable location of industrial electrical distribution systems.

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